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14. ABSTRACT

This project's dual objectives are the preparation of the PI for a career in breast cancer research and the design of a system of computer-base simulations capable of evaluating the effectiveness of various methods of breast cancer brachytherapy treatments both in general and for each individual patient for use in clinical decision-making. PI was trained in the use of the ABAQUS software package to finish the Finite Element portion of the project as well as acquiring additional computing resources to facilitate and streamline the remaining parts of the project. Using these resources, models of the various treatment devices were created with manufacturer specifications and tested in an idealized tissue model of a breast demonstrating adequate similarity to documented physical behavior. Work was then started on creating breast models from patient data to reflect geometry and approximate tissue inhomogeneity. This work is still in progress.

15. SUBJECT TERMS
Monte Carlo Simulation, Medical Physics, Radiation, Brachytherapy, Breast Cancer

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Introduction

This project's dual objectives are the preparation of the PI for a career in breast cancer research and the design of a system of computer-base simulations capable of evaluating the effectiveness of various methods of breast cancer brachytherapy treatments both in general and for each individual patient for use in clinical decision-making. This will be achieved by developing a system that automatically generates models of patients using clinical data and allowing the user to explore various treatment options in the most realistic way possible, considering all physical interactions in order to accurately estimate and compare dose in any specific patient geometry for different devices. Once this is accomplished the system can be adjusted to be as close to real time as possible for ease of incorporation into treatment planning. The specific aims of the this project are:

SA0. Take the appropriate courses and acquire training to be become a professional Medical Physics researcher.

SA1. Develop Finite Element Method (FEM) tools to simulate the interaction between brachytherapy PBI devices and breast tissue.

SA2. Develop Monte Carlo Simulation (MCS) tools to estimate radiation dose distribution produced by a particular brachytherapy PBI device.

SA3. Compare the dosimetric features of all brachytherapy PBI devices for 10 breast cancer patients of various representative breast geometries using FEM and MCS tools developed in SA1 and SA2.

Body

I. Timeline

Activities		Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Courses/Study	Cancer biology	■	■										
	Radiation biology			■	■								
	Radiotherapy Physics			■	■								
	Medical Imaging	■	■	■	■								
Clinical Skills	Delivery Methods	■	■										
	Treatment Planning			■	■	■	■						
	Special Procedures					■	■	■	■				
	Machine Commissioning					■	■	■	■				
	Machine Quality Assurance					■	■	■	■				
Laboratory Techniques	FEM					■	■	■	■				
	MCS	■	■	■	■								
	Parallel Computing	■	■	■	■								
	Software Development									■	■	■	■

II. Courses/Study

SA0. Take the appropriate courses and acquire training to be become a professional Medical Physics researcher.

Additional courses were taken in order to familiarize the PI with the finite element software, ABAQUS, used for SA1.

1. Introduction to ABAQUS (a three-day introductory course provided by the manufacturer).
2. Stent Modeling and Analysis Methodology (an online seminar provided by the manufacturer)

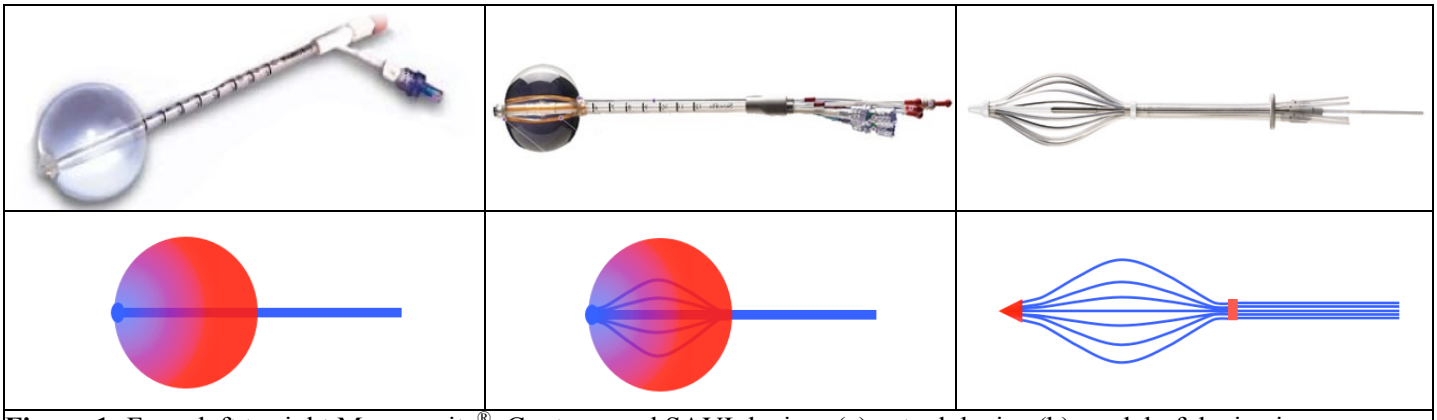

Figure 1: From left to right Mammosite®, Contura, and SAVI devices (a) actual device (b) model of device in

ABAQUS.

III. Parallel Computing

An additional 35,000 computing hours and access to the ABAQUS software package were approved at the San Diego Super Computer center on the significantly faster Trestles cluster.

IV. Finite Element Model

SA1. Develop Finite Element Method (FEM) tools to simulate the interaction between brachytherapy PBI devices and breast tissue.

A. Device Modeling

Using manufacturer material and dimension specifications, models were developed for the three major breast-brachytherapy devices currently available: Mammosite®, Contura, and SAVI (figure 1) as well as interstitial catheters (Figure 2).

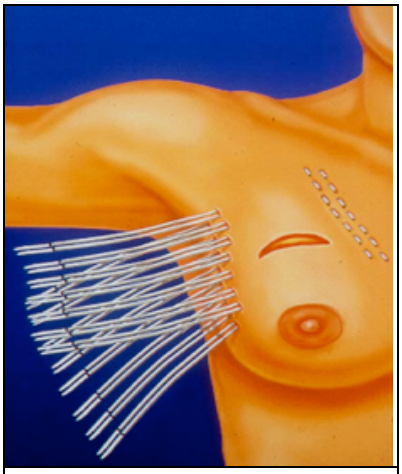

Figure 2: An interstitial catheter brachytherapy setup

The devices began as simple geometrical approximations, including only the necessary parts. Interstitial catheters were the simplest being only a series of tubes. For the MammoSite and Contura devices, this included the center catheter, auxiliary catheters for the Contura and the balloon. For the SAVI this included the center catheter and surrounding struts as well as the constraint at each end that allows the device to expand. Parts were added incrementally in order to appropriately model and behavior the real devices while working within the complexities and constraints of the software. Any non-physical behavior such as unrealistic bending or materials and objects overlapping in space triggered adjustment to the model.

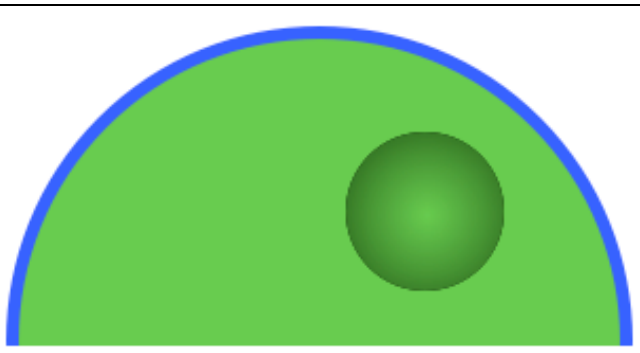

Figure 4: Simplified model of the breast for testing devices shown as a cross section. Blue represents skin, while green is approximately like adipose tissue. The lumpectomy is also idealized as a sphere.

The balloons were be modeled by applying a uniform force of their surface area from the inside, thereby avoiding a computationally expensive fluid simulation while still closely mimicking their expected behavior when applied to breast tissue.

Of special interest was the superelastic/plastic behavior of Nitinol, which composes the struts of the SAVI and Contura devices. As the models of these devices, particularly the SAVI need to move realistically in order to determine the displacement and density change of the surrounding tissue, the struts needed to be modeled such that applied force would yield the correct deformation and consequently the proper shape.

Table 1

	Length (cm)	Width (cm)	Volume (cc)
MammoSite 4-5cm	4.00-4.65	4.00-5.10	34-77
MammoSite 5-6cm	5.11-5.73	4.87-5.90	70-125
Contura	4.75	4.50-6.00	40-100
SAVI 6 strut	5.50	3.00	15-30
SAVI 8 strut	6.00	4.00	30-60
SAVI 10 strut	6.50	5.00	60-90

Simulations of balloon and catheter devices exhibited expected behavior when force was applied to catheters

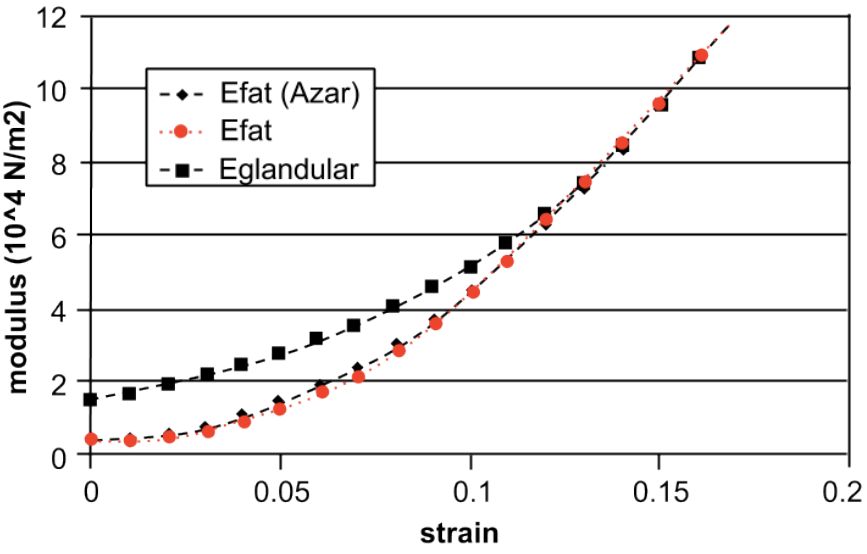

Figure 3: Comparison of our tissue model for fatty tissue in ABAQUS with the tissue model in Azar et al.

devices) meaning that the parts of the device moved in a realistic, physical manner when displacements of various points (range of length and width when inflated or expanded) as well as volume of the expanded device were compared to the actual measured dimensions of the devices (table 1). Simulated devices were considered valid if they could cover the range of dimensions within 10%.

Devices were then tested in an idealized, homogenous tissue model where the breast was approximated as a half sphere skin as the surface of the rounded part of the half sphere and the rest as adipose tissue (figure 4). Results of these tests also demonstrated expected behavior compared to existing literature (Azar et al. 2002) when matching the displacement of points within the tissue model to the amount of force applied by the device for the Mammosite and Contura devices (see table).

B. Tissue Modeling

Patient CT data post lumpectomy, but before device insertion has been acquired and converted to a mesh to be imported into the ABAQUS software. This tissue is initially being treated as homogenous and modeling of device insertion into the tissue will be the next phase of this part of the project before exploring more complex tissue models in which fat/adipose tissue is defined separately from glandular tissue. This will first be addressed in the simpler, geometric model as the additional boundary condition constraints add a considerable amount of time to the calculations. Comparing them to the post-device-insertion scans will validate these patient models.

V. Monte Carlo

SA2. Develop MCS tools to estimate radiation dose distribution produced by a particular brachytherapy PBI device.

A more accurate tissue model created for the Monte Carlo simulation, indicated that, while dose was still higher in the target region near the air-tissue interface, it was not as high as previously calculated.

Material and Methods

Data from TPS plans for 21 patients were used including CT image data, contoured structures and source information.

Phantom Description

CT images were imported into the PENELOPE code as voxel files where the various densities were determined by calibrated Hounsfield unit data from the CT scanner and the materials were determined by the contoured structures from the treatment plan. Four materials were used based on their distinguishability from each other due to the strength of their interaction with the 192Ir energies. (Bazalova et al.) These materials

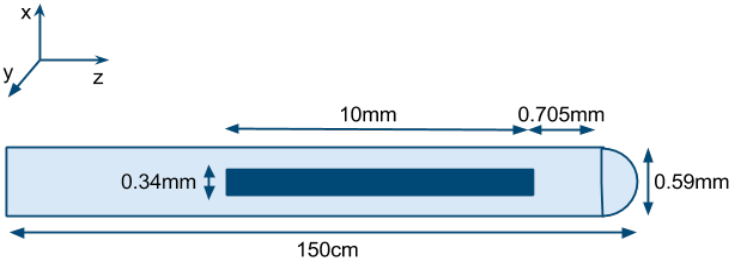

Figure 5: VariSouce Schematic of 192Ir seed.

Source Description

The source used was the VariSource 192Ir (Karaiskos et al.) with gamma and fluorescence x-rays from the NuDat database. Photons with intensity less than 0.1% and x-rays with energies below 10 keV were omitted as transmission of these through the 0.0125 cm nitinol capsule would be negligible (Casado et al.) and it saved a great deal of time in the simulation. The source model shown in figure 5 was created as a quadric structure consisting of a 10 mm long cylindrical capsule with semispherical ends and a diameter of 0.34 mm encased in wire 0.59 mm diameter also with a semispherical end. The wire extends 1 mm beyond the active core and 150 cm in the other direction. Only 1 cm is used in the simulation for simplicity, since there are many source dwell positions being simulated. In order to ensure that this did not affect the overall accuracy of the simulation, we compared dose differences between source models with different trailing wire lengths ranging from zero to twenty centimeters and found the difference anisotropy to acceptable (figure 6) with most of the dose difference landing within the wire itself, an area not counted when measuring the dose to a patient.

Source positions with orientations were extracted from the original plan. The positions were given in Cartesian coordinates and the orientation was determined using the tangent to the structural plot of each strut of the device (figure 7).

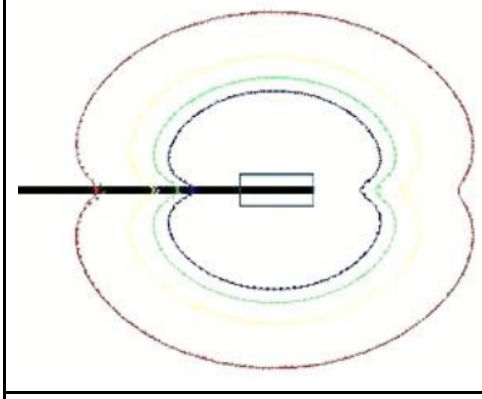

Figure 6: Difference between 1 and 20 cm trailing wire off of source where the source length is indicated by the box in the center, the dotted line represents dose for the 20 cm trailing wire and the solid line represents dose for the 1 cm trailing wire and the blue, green, yellow and red lines represent 200, 150, 100, and 50% of the prescribed dose.

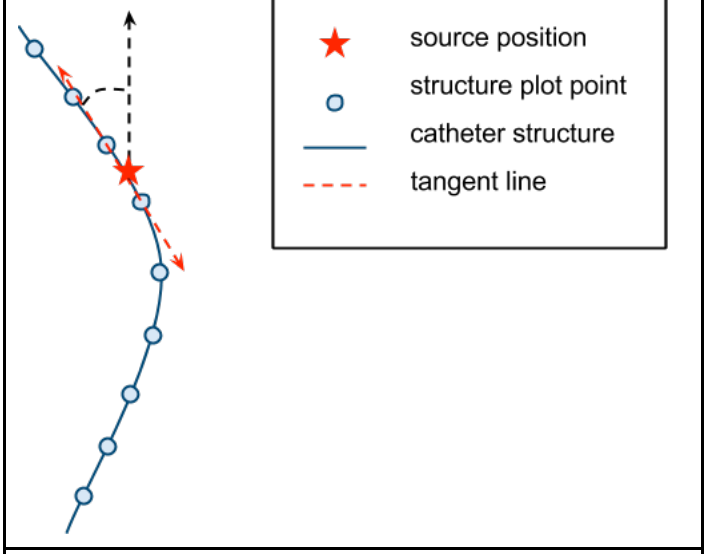

Figure 7: Determination of source orientation using structure data. The structure of each catheter was given as a set of points. These points are plotted as a line in Matlab and then the tangent of that line is taken at each source position.

Monte Carlo

These simulations were run on the Trestles cluster at the San Diego Supercomputer Center using the 2008 PENELOPE software including penEasy and clonEasy packages. Each source position was run independently in the same phantom and then weighted according to its dwell time at that position before all simulations were summed voxel by voxel to find total dose. This was done with a voxel size of 0.6x0.6x0.6 mm. The simulation was set to generate histories until a sigma value of <0.5 was achieved. The average number of histories it took to achieve this was on the order of 10^9.

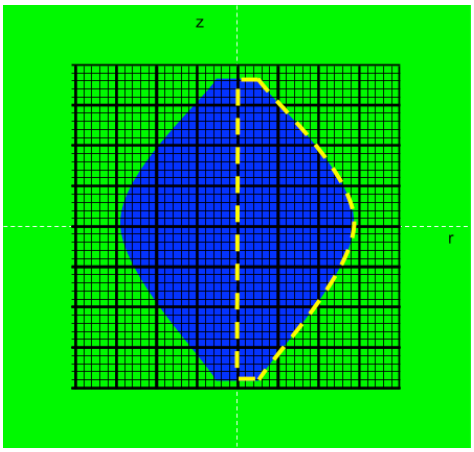

Figure 8: 10 strut SAVI model.

Actual Dose was calculated using the formula $D_i = A \cdot t \cdot f \cdot D_i^{MC}$ where D_i is the actual dose in eV/(g*histories), A is activity in disintegrations/sec, t is time, and f is a calibration factor determined by comparing a simple source model MC simulation with one from the TPS.

Validation

In order to validate the accuracy of the simulation, a MC simulation of single source in water was compared to both to a TPS simulation of a single source in water and to results from a prior publication [2] of a single source in both water and water with an air cavity both using MC and ion chamber data.

TPS

For comparison of the single source in water done via MC and TPS, a 30x30x30 cm water phantom was used with voxel size was 0.6x0.6x0.6 mm. 2.3x10^9 histories were run and the results were compared with corresponding TPS results.

Literature

For comparison with MC and ion chamber data a phantom was created to simulate a ten-strut device containing an air cavity in a cylindrical water phantom 40 cm tall with a radius of 20 cm see figure 8). Voxel size was 2x2x2 mm and aproximately 1.7x10^9 histories were run for each simulation. The simulation was run with and without the air cavity.

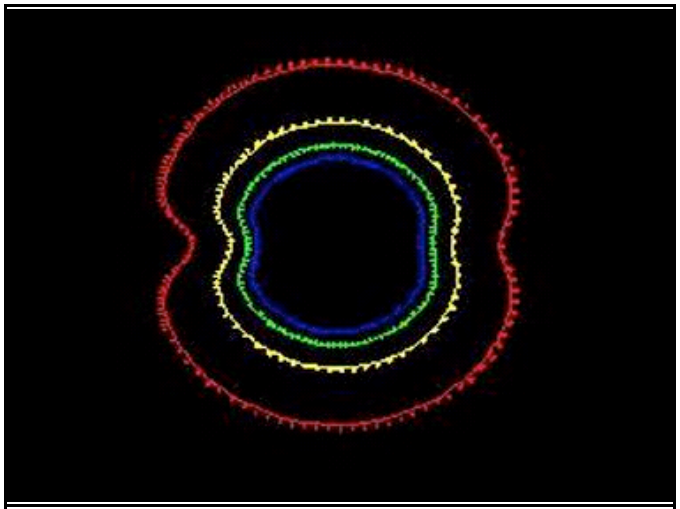

Figure 9: Comparison of isodose lines representing percent of the prescription dose (34 Gy) for a source in water where red is 50%, yellow is 100%, green is 150% and blue is 200%. The solid and dashed lines represent TPS and MC results, respectively.

Results

Validation

TPS

The TPS was used to test and calibrate the source model. The shape of the isodose lines matched well with the TPS results and the dose was close to the calculated dose when calibrated for activity. Plotting the isodose lines for the TPS versus the source model as seen in figure 9 shows the similarity of the results from the MC source model to the TPS results including symmetry and anisotropy. Subtraction analysis of the two doses (where dose is compared voxel by voxel) gives an average different of 0.1% and a maximum difference of 0.78% where the uncertainty value for the simulation is 0.4%.

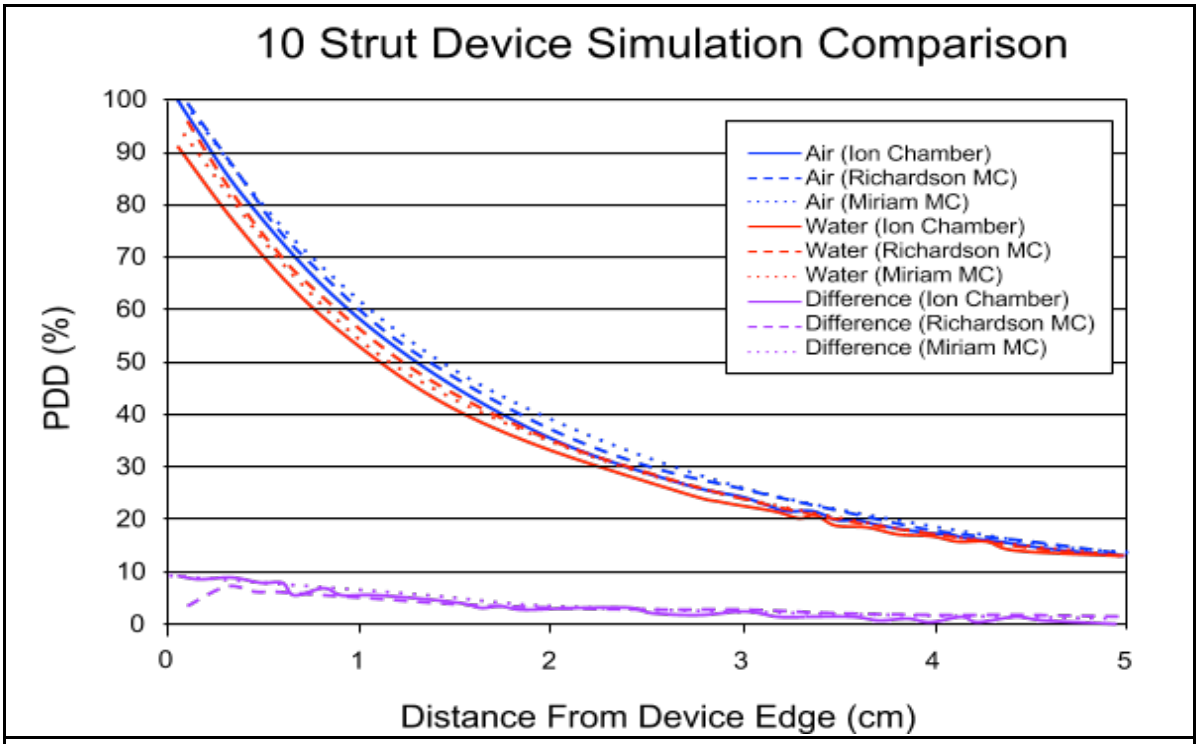

Figure 10: Comparison of MC simulation (dotted) with MC (dashed) and ion chamber (solid) results from Richardson et al. both with (blue) and without (red) an air cavity, as well as the difference between the two (purple).

Literature

Comparison to the model from Richardson et al can be seen in figure 10. The simulation yields similar results to Richardson et al. although our MC results are closer to their ion chamber results, particularly since there is no dropoff near the edge of the balloon for the MC simulation.

Monte Carlo

Isodose Line Analysis

Dose from the Monte Carlo plan was compared with dose from the original plan using isodose lines at 50, 100, 150 and 200% of the prescription dose of 34Gy. The lines were then plotted on the patient phantom in order to compare

Dosimetric Coverage

Dosimetric coverage of the target was also compared by evaluating the V150 and V200 (volume of the target covered by 150 and 200% of the dose respectively) and the V100 (percent of the target covered by 100% of the dose). The V150 and V200 had an average increase (and standard deviation) of 3.8% (1.4%) and 9.1% (3.2%) respectively, while the average change in V100 was 1.2% (1.0%).

Uncertainty Analysis

Although on average 2*10^10 histories were run for each full simulation in relatively small voxels, the variance was 0.9% which, while acceptable for most MC, introduces relatively large variations when comparisons, ratios or absolute differences are computed.

VI. Incorporation of Finite Element Model with Monte Carlo

SA3. Compare the dosimetric features of all brachytherapy PBI devices for 10 breast cancer patients of various representative breast geometries using FEM and MCS tools developed in SA1 and SA2.

A total of 22 patient data sets were acquired for this purpose, of which 10 can be selected. A model is currently being developed to use this data with the devices created in the FEM. Once the FEM model is complete, this will be interfaced directly with the MC simulation.

Key research accomplishments

- Improved model of MC simulation indicated that increase in dose was lower than previously thought
- Model devices developed in FEM code showed expected physical characteristics during tissue interaction.

Reportable outcomes

1. Oral Presentation: AAPM 54th Annual Meeting July 29- August 2 Charlotte, NC
   Evaluation of the Dose Calculation in a Commercial Planning System for a Breast Cancer Brachytherapy Technology Using Monte Carlo Simulation
   M. Graf*, L. Cervino, D. Scanderbeg, C. Yashar, S. Jiang

2. Grant Awarded: 35,000 SUs on the Trestles Cluster at the San Diego Super Computer Center.

Conclusions

In conclusion, SA2, the Monte Carlo portion, has been improved and amended and work has been initiated on both SA1 (the Finite Element Model) and SA3 (incorporating the FEM and MC portions). In the next year the PI will complete both of these tasks early in the year and begin the process of writing and defending a thesis based on this work.

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Appendix A: AAPM 54th Annual Meeting Abstract

Evaluation of the Dose Calculation in a Commercial Planning System for a Breast Cancer Brachytherapy Technology Using Monte Carlo Simulation

M Graf[1,2,3]*, L Cervino[1,2], D Scanderbeg[1,2], C Yashar[1,2], S Jiang[1,2], (1) Center for Advanced Radiotherapy Technologies, University of California San Diego (2) Department of Radiation Medicine and Applied Sciences, University of California San Diego (3) Department of Physics, University of California San Diego

SU-D-213AB-4 Sunday 2:15:00 PM - 3:00:00 PM Room: 213AB

Purpose: To evaluate the dose calculation in a commercial treatment planning system (TPS) for a breast cancer brachytherapy technology using Monte Carlo simulation for 21 patients.

Methods: Plans for 21 patients who received SAVI treatments were modeled using data from the TPS including CT images, structures and source information. The MC code PENELOPE was used, inputting images in voxel format, where density and material (tissue, air, bone and Nitinol) for each voxel were assigned based on its calibrated Hounsfield units and contoured structure sets, respectively. For the source model only gamma-rays and fluorescence X-rays of the NuDat database 192Ir spectrum were used, leaving out photons with emission intensity less than 0.1% and X-rays with energies below 10 keV. Source positions were entered into the plan and run individually. Dose was totaled by individually weighting the dose for each source position using the original TPS plan dwell times and then summing the weighted dose for all positions.

Results: Dose from the Monte Carlo plan was compared with dose from the original plan using isodose lines at 50, 100, 150 and 200% of the prescription dose of 34Gy. Dosimetric coverage of the target was compared by evaluating the V100, V150 and V200 (volume of the target covered by 100%, 150 and 200% of the dose respectively). The V200 and V150 had an average increase (and standard deviation) of 9.1% (3.2%) and 3.8% (1.4%) respectively, while the average change in V100 was 1.2% (1.0%). Where variance for the entire simulation was 0.9%.

Conclusion: We have compared dose distributions of a commercial TPS using Monte Carlo simulation for SAVI breast cancer brachytherapy and found that a dose increase near the air-tissue interface.